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XV.

CONTRIBUTIONS FROM THE PHYSICAL LABORATORY OF HARVARD COLLEGE.

No. VIII.—ON THE INDUCTION SPARK PRODUCED IN BREAKING A GALVANIC CIRCUIT BETWEEN THE POLES OF A MAGNET.

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Becquerel, in the "Journal de Physique," IV. 206, states that the spark obtained by breaking the current, which circulates through an electro-magnet between its poles, is entirely a mechanical effect.

To test the accuracy of M. Becquerel's result, I placed in the same circuit four Grove cells, an electro-magnet of the form used in experiments upon Diamagnetism, and a coil of coarse wire wound around a bundle of iron wires on a core. Over this coil was slipped an induction coil of 6000 ohms resistance.

I first experimented upon the spark given by the induction coil when the primary circuit was broken between the poles of the electro-magnet, and then outside of them.

The number of cells in the circuit was varied, and its resistance was several times changed, in order to vary the circumstances as much as possible; and, at each change, a series of observations were taken to see whether the spark from the induction coil had any greater power of overcoming resistance when the primary circuit was broken between the poles of the magnet.

A long series of observations on sparks, which were of all lengths from 2½ to 15 mms., justifies the statement that the distance over which the spark of the induction coil would regularly leap was more than *doubled* when the circuit was broken between the poles. The absolute length of spark obtained depended, of course, on the electromotive force in the primary circuit being apparently within certain limits directly proportional to it. In almost all cases, the length of spark was increased three or four times; but in no one set of observations was the spark less than doubled in length. These experiments were repeated several times on different days.

I found great difficulty in breaking the primary circuit uniformly, and it was only after a long time that my results became regular.

I tried breaking from the surface of mercury; but, although the same relative effects were attained, the actual effect was far inferior to that obtained when two bright copper wires were separated in the air.

Rowland has shown that a very powerful electro-magnet is not needed, in order to obtain good results in studying Diamagnetism. In order to see whether a small magnet would not do to increase the length of the spark, a small electro-magnet, capable of supporting perhaps two kilogrammes, was set up, and a series of observations taken when the circuit was broken between its poles. In this case, the length of the spark was just doubled. Might not a rather small horseshoe electro-magnet be advantageously placed upon the Ruhmkorff coil, so that the primary circuit should be interrupted between its poles?

I next put the electro-magnet in one circuit, and broke another circuit containing the primary of the induction coil between the poles of the magnet. With this arrangement, two sets of observations were taken under slightly different circumstances. The results are given below in the actual space over which it was found that the sparks would just pass. The words " outside " and " inside " denote that the primary circuit was broken outside of the poles and between them respectively.

Outside.	Inside.
2½ mm.	12½ mm.
3 „	20 „

Of course the relative increase in the length of the sparks depended upon the relative strengths of the two currents. When the electro-magnet is very weak, and the outside current very strong, subsequent experiments showed that there was little, if any, increase in the length of the spark.

As a direct means of showing that the extra effect obtained by breaking between the poles is not mechanical, the following method was employed. The electro-magnet was placed in a circuit with two Grove cells. To the end of one of the large wires used for breaking the circuit a very fine wire was fastened, leading to one pole of a Thomson's Quadrant Electrometer, whose other pole was put to earth. Whenever the two large wires were separated, there was of course a deflection of the electrometer mirror corresponding to the difference of potential of the poles of the battery; but, beside this, there was an increased effect when the circuit was broken between the poles, that seems to be unaccountable, if we assume the effect to be mechanical.

When a condenser of about 1 Farad capacity was put into the circuit, the following deflections were obtained: —

Primary broken outside.	Primary broken inside.
21	27
20.5	28
22	28
20	27
Mean 20.9	27.5

When no condenser was used, the deflections were as follows: —

Primary broken outside.	Primary broken inside.
20	22.5
19	23.5
20	23.5
20	24.
19.75	23.4

The electro-motive force in the circuit was very small, hardly enough to render the poles strongly magnetic. With a proper electro-motive force, we might expect the effects to be more striking.

In order to measure the increase of quantity obtained by breaking the primary circuit between the poles of the magnet, the electro-magnet and the primary of an induction coil were placed in the same circuit as at first. The poles of the induction coil were connected, the one directly, the other by means of the spark leaping between two points with a condenser of $\frac{1}{3}$ Farad capacity. The poles of the condenser were connected with a Thomson's galvanometer of 5880 ohms resistance. Each of the following results is the mean of two observations. The length of spark was the same in both cases.

	Primary broken outside.	Primary broken inside.
6 cells.	17.5	21.05
4 „	12.	17.

The resistance of the six cells (Bunsen) was greater than the resistance of the primary circuit.

On another day, the same arrangement gave the following result, where each is a mean of two observations : —

Length of spark.	Primary broken outside.	Primary broken inside.
1 mm.	22	30
3 „	12	23

In a great many cases, where the magnet was quite powerful, it was not easy to get comparable results. When the primary circuit was broken between the poles, the spot of light was driven off the scale; but, when the primary was broken outside, there was frequently very little deflection.

At another time, a Thomson's mirror galvanometer of 6 ohms resistance gave, with an arrangement otherwise the same as above, the following deflections as a mean of twelve observations : —

Outside	12.9	Inside	15.37.

When the electro-magnet was in a separate circuit from the primary of the induction coil, the following observations were obtained with the Thomson's galvanometer. Each result is the mean of about twenty observations.

Length of spark.	Primary broken outside.	Primary broken inside.
1 mm.	21	35.8
2 „	20	23
3 „	16.5	19.9
4 „	15.2	17

All these results were taken, interrupting the primary circuit by separating two copper wires held one in either hand. Practice made the results then obtained quite accurate. I at first tried breaking from the surface of mercury; but, beside the irregularity in the amount of the deflection, there was a most unaccountable change of polarity every few moments. I distrusted the evidence of my own senses so much in this case that I asked several other people to observe for me, without previously telling them any thing of this change of polarity. In each case, the observer noticed the reversal for himself. The deflection was almost always in one direction when the circuit was broken between the poles, and in the other direction when the circuits were broken outside of the poles. This rule is not, however, absolute. This reversal of polarity only occurred when *copper* was used to break from the surface of the mercury. The separation of iron from iron, or copper from copper, or iron from mercury, never gave any reversal. This reversal was best seen with the electrometer.

At several different times, I took a series of observations upon the deflection, by breaking inside the poles and outside of them when the distance over which the spark had to leap was varied. The curves obtained by laying down these deflections were not, as one might suppose, hyperbolas, but were apparently exponential curves, having the axis of x as an asymptote, but not the axis of y. A series of very careful observations was taken by observing the deflections when the distances over which the spark passed were small. The curves obtained by breaking the primary between the poles were similar to those obtained when the primary was broken outside. The observations were taken by breaking the primary with the interrupter of one of Ritchie's induction coils. The sparks passed between two circular discs of copper 10 cm. in diameter. In the centre of one of the discs was an almost imperceptible protuberance, in order to insure the sparks always passing in the same place. One plate was fixed in a horizontal position; the other was suspended, by a thin ivory handle perpendicular to its plane, to a glass rod placed in the telescope socket of a cathetometer. In this way, it was found possible to get the plates sensibly parallel. The poles of the induction coil were connected with a condenser; one directly, and the other by means of the spark passing between the two discs. The condenser was then discharged through a galvanometer. The micrometer screw of the cathetometer reads easily to the $\frac{1}{1000}$ of a millimetre, and observations were taken with its aid at intervals of .050 mm. The plates were considered to be in contact, whenever *making* the primary circuit gave any deflection in the galvanometer. The zero thus obtained was quite constant, whereas it was almost impossible to tell by the eye just at what point the spark ceased to pass when the circuit was broken. The poles of the battery were kept apart when not actually in use, and it was supposed that the electro-motive force remained constant during the time of observation.

In laying out a curve, it must be remembered that there was a resistance of 6000 ohms already in the circuit. Each of the following results is the mean of a series of closely agreeing observations: —

Separation of plates in mms.	Deflections.
.050	183
.100	176
.150	164
.200	145
.250	130
.300	136
.350	123
.400	127
.450	120
.500	106
.550	102
.600	97
.650	92
.700	88
.750	90
.800	91
.850	95
.900	96
.950	88
1.	93
1.050	79
1.100	85
1.150	84
1.200	70
1.250	75
1.500	63
1.750	51
2.000	50
2.250	45
2.500	42

When the sparks passed between the ends of two copper wires, ⅔ mm. in diameter, carefully filed so as to be parallel, the curves obtained were very regular, but of the same general shape. As an example, I give the following: —

Dist. over which the spark leaped in mms.	Deflections.
1	90
2	70
3	55
4	44
5	35.6
6	27
7	20
8	13
9	7
10	2.5
11	1.4
12	.8

Sir William Thomson has shown, in his paper on the "Electro-motive Force necessary to produce a Spark," that a greater force per unit of length is needed for short distances than for long distances. He does not state in his paper whether he experimented upon the Ruhmkorff coil or the Holtz Machine. In using the Quadrant Electrometer in measuring the electro-motive force of the sparks from an induction coil, it is, of course, necessary to use a small leaping distance from the sparks to avoid the return current. At times, I have found that a greater actual deflection was obtained when the leaping distance was as great as ½ mm. than when it was much smaller. May not Sir William Thomson's results be partly accounted for by induction in the same manner?

Another method of experimenting upon the extra spark obtained by breaking the circuit between the poles of an electro-magnet gave excellent results. One of the poles of the induction coil was connected with the outer coating of a very small Leyden jar; while the other pole connected with the inside coating through a small interval of air, to avoid the return current. The inside coating of the jar was connected by a very fine wire to a thin copper disc, 261 mms. in diameter. Opposed to the copper disc, at a perpendicular distance of 160 mms., was the end of a short rod, 1 mm. in diameter. Attached to the other end of the rod was a very fine wire connecting with one pole of the

Quadrant Electrometer. The other pole of the electrometer was connected with the ground. The very fine wire leading from the opposing section of the rod was so arranged that experiment showed no inductive effect from the disc upon it. When the primary circuit was broken, a spark passed charging the Leyden jar, and consequently the circular plate. The insulated plate was consequently charged to some constant potential V_0.

According to Maxwell's Electricity, Vol. I. § 177, and Thomson's "Papers," 233, the surface density at any point on a thin circular insulated plate is —

$$\sigma = \frac{V_0}{2\pi^2\sqrt{a^2-m^2}}$$

where a^2 is the radius of the plate, and m the distance of the point from the centre.

If the plate is in the co-ordinate plane $x\,y$, we have, —

$$\sigma = \frac{V_0}{2\pi^2\sqrt{a^2-x^2-y^2}}$$

The potential at any point (x, y, z) in space due to this distribution is $\int\int\frac{dy\,dy\,\sigma}{r}$, since the plate is thin. The limits must be so chosen as to comprehend the whole surface of the disc, and to avoid errors the point (x, y, z) must be opposed to the disc.

$$r^2 = (x - x_1)^2 + (y - y_1)^2 + z^2$$

$$V_{x,y,z} = \int\int\frac{V_0}{2\pi^2}\cdot\frac{1}{r}\,\frac{dx\,dy}{\sqrt{a^2-x_1^2-y_1^2}}$$

At any fixed point (x_1, y_1, z_1), therefore, the potential is proportional to V_0. It was supposed necessary that the potential of the quadrants attached to the short rod, which was at a great distance from the electrometer, would be proportional to V_0. The opposite quadrants were at potential zero, being connected with the earth; and since, when the deflections are small they are proportional to the difference of potential of the two poles of the instrument, it was supposed that the deflection of the electrometer needle would be a relative measure of the potential of the plate.

A great many observations were taken with this apparatus, and the results agreed with the former ones, not only qualitatively, but very nearly quantitatively. I select the following series of observations to show this. The difference is in this case not so widely apparent, owing to the extreme weakness of the current used; it being at this time, in order to get small deflections, the weakest used in the whole of my work.

Primary broken outside.	Primary broken inside.
7.5	9.5
10.	9.
7.3	9.4
7.	9.5
8.2	8.5
8.2	9.2
10.6	9.5
9.5	8.6
5.2	8.4
10.	9.7
8.8	8.5
8.	9.4
6.5	10.5
9.4	10.9
7.	8.1
9.2	10.
5.3	8.7
10.5	12.
8.3	7.8
8.5	8.4
9.8	10.6
9.9	8.6
Mean 8.4	Mean 9.3

These were taken in sets of ten, with wonderfully close means, notwithstanding the apparently great probable error.

Another series, with a stronger current, gave as the ratio of the results 1.364.

The results of the investigation are as follows: —

1. By breaking the primary circuit of an induction coil in a magnetic field, the length of spark produced by the secondary coil is more than doubled in length. An application of this fact to the induction coil is suggested.
2. The results by the different methods used all show an increase of electro-motive force when the circuit is broken in a magnetic field; and that the effect cannot be purely a mechanical phenomenon, as M. Becquerel affirms.

3. By breaking the circuit between mercury and copper in the magnetic field, a remarkable change of polarity was observed with the electrometer.
4. An explanation is offered of the fact noticed by Sir William Thomson, that a greater electro-motive force per unit of length is needed to produce a spark at a short distance than at a long one.

The subject of this paper was suggested to me by Professor Trowbridge, and throughout all my work he has kindly given me his advice and help.